RESEARCH REPORT

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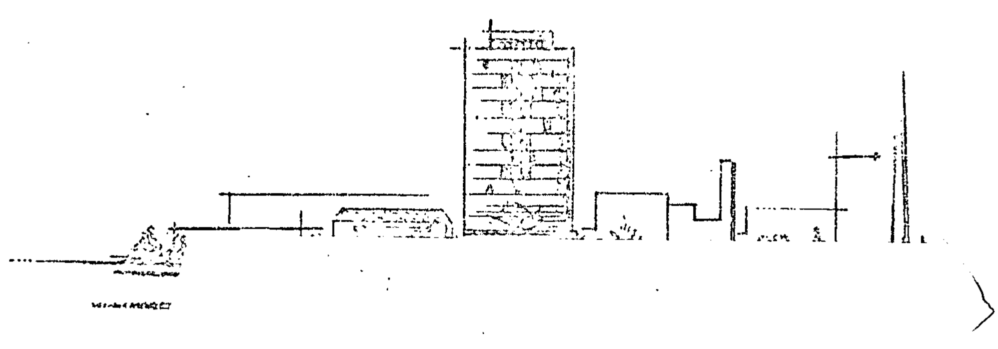

BATTELLE MEMORIAL INSTITUTE

COLUMBUS LABORATORIES

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40p

FINAL TECHNICAL REPORT

on

SPECIAL PROBLEMS RELATED TO MATERIALS, PROCESSING, AND OPERATION OF SLIP-RING ASSEMBLIES USED IN ST-124M STABILIZED INERTIAL GUIDANCE PLATFORM

to

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER, ALABAMA

November 30, 1968

by

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Period of Report
October 1, 1964 to November 30, 1968

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FOREWORD

The research summarized in this report was carried out under contract NAS 8-11403. This contract covered phases of work at Battelle not directly related to slip-ring contact problems. Only the results of the research directly related to the contact problems are reported here; other reports have summarized the remainder of the work.

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SPECIAL PROBLEMS RELATED TO MATERIALS, PROCESSING, AND OPERATION OF SLIP-RING ASSEMBLIES USED IN ST-124M STABILIZED INERTIAL GUIDANCE PLATFORM

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INTRODUCTION

As revealed in inspection evaluations, difficulties have been encountered with the contacts in slip rings used to deliver electric power and control signals to the ST-124M inertial guidance platform associated with the Saturn V system. After some period of operation – sometimes as short as a few hundreds of hours – high resistances develop in the contacts. In many instances the increased resistance is a consequence of deposits (commonly referred to as friction polymers in the literature) which form when metallic surfaces are rubbed against each other in the presence of organic vapors. During the period from October, 1964, to May, 1968, Battelle performed an investigation to determine what organic materials in, and near, the slip-ring assemblies needed to be modified or replaced in order to eliminate the contact deposits. The results, conclusions, and recommendations of the contact-deposit investigation were presented in the Interim Summary Report on this program.

As the contact-deposit investigation progressed, it became clear that the particular contacts (Neyoro 28A* wire brushes and electrodeposited gold armature rings) employed in the ST-124M slip-ring assembly or capsule would suffer severe wear damage if the offending organic vapors were eliminated from the contact environment. With this result, the above investigation was expanded to include a second phase, consisting of a program designed to identify the most promising liquid lubricating material for plated-gold/Neyoro 28A contacts. This second-phase investigation revealed a number of factors that are important in choosing and evaluating a lubricant for low-energy electrical contacts. The outcome of the lubrication phase of the overall program was the identification of a blend of lubricants, 75 percent OS 124** and 25 percent MCS 210**, as the material most likely to provide satisfactory performance in actual slip-ring applications. The program discussed above demonstrated the suitability of the recommended blend for lubricating simulated slip-ring contacts and, at the same time, revealed four specific areas in which additional knowledge was required to apply the previous findings to the lubrication of actual slip rings. Consequently, a supplemental program was initiated to carry out the tasks listed.

(1) Lubrication Repeatability Studies. Ten separate sliding-contact pairs operating for 10^7 wipes at room temperature and ten pairs operating for 10^7 wipes at 43 C were to be lubricated with the blend of lubricants and the dynamic resistance measured.

*J. M. Ney Company, Bloomfield, Connecticut.

**Monsanto Chemical Company.

(2) Wear-In Studies. The object of this task was to determine how subsequent wear depends on the initial wear conditions.

(3) Short-Stroke Studies. Anomalous resistance values seemed to be occurring when sliding Neyoro 28A/plated-gold contacts were operated in a regime in which the wiper (brush) moved over a distance in the neighborhood of 0.002 inch.

(4) Lubricant Shielding Ability. In the absence of an intentionally added lubricant, deposits form on the sliding contacts operated in the presence of certain organic vapors. The goal of this task was to determine what protection, if any, the intentionally added lubricant afforded the contact. (The extent to which the amount of organic vapors needs to be reduced in the slip-ring atmosphere depends on such information.)

The results of the investigation concerned with the four tasks are given in this final report on the total program. Since the Interim Summary Report summarizes the work of the entire program through May 31, 1968, details discussed in that report are not repeated here. For those details, the reader is referred to the interim report. However, the essential conclusions and recommendations are repeated here so that the major conclusions and recommendations of the total program are contained in one place.

There are occasional references to the "original investigation" or to the "interim report" in the body of this final report.

SUMMARY

This final report presents the results of supplemental studies conducted to verify and expand specific findings of a larger and more general study completed May 31, 1968. The specific tasks of the supplemental studies were (1) to verify the suitability of a special blend of lubricants (developed as a part of the more general study) for lubricating gold/Neyoro 28A slip-ring contacts by conducting a statistically meaningful number of experiments under standardized conditions, (2) to determine whether techniques could be devised for preconditioning slip-ring contacts so that they could perform satisfactorily over a wider range of temperatures, (3) to determine the cause of very short duration noise spikes that were known to occur when lubricated contacts were rubbed with very short strokes, and (4) to determine whether the recommended lubricant blend would shield the contacts from organic vapors known to cause harmful deposits on unshielded contacts.

It was found that sinusoidal wiper motion, with a maximum wiper speed of about 0.9 cm/sec, caused large hydrodynamic-lift effects in more than half of the contacts evaluated at ~23 C. Thus, these operating conditions represent a limit beyond which satisfactory operation cannot be expected. If the maximum wiper velocity is reduced to ~0.5 cm/sec, all contacts can be expected to perform satisfactorily. When the contact temperature approaches 43 C, contact between the wiper and an experimental contact flat is such that stick-slip effects occur and cause very short duration noise spikes. It is believed that the stick-slip behavior is highly dependent upon contact geometry, and probably will not occur for the geometry of actual slip-ring contacts. The same behavior

was shown to be responsible for short-duration noise spikes encountered in short-stroke contact operation. Here too, it is anticipated that the geometry of slip-ring contacts will minimize or eliminate this problem. At any rate, it was shown that the presence of the lubricant greatly reduces the tendency of contacts toward stick-slip spikes over that encountered with unlubricated contacts.

About 10^5 wipes with contacts operating at 43 C and maximum wiper velocity, ~0.9 cm/sec, greatly reduce the effects of hydrodynamic lift of the wiper during subsequent operation at room temperature.

Finally, the presence of the lubricant blend retards or reduces the effects upon the electrical behavior of deposits formed on contacts exposed to an atmosphere containing harmful organic vapors. The lubricant does not, however, eliminate the formation of contact deposits.

STATEMENT OF THE PROBLEM AND DISCUSSION OF RESULTS OBTAINED IN EARLIER WORK*

Achievement of the lowest possible electrical contact resistance requires metal-to-metal contact. For low-energy contacts, it is essential that the resistance be kept small; that is, thick films of poorly conducting materials between the contacts cannot be tolerated. This means that some metal-to-metal contact and its consequential wear must be accepted even when the contacts are lubricated. The original investigation established that a number of liquid lubricants were capable of holding the wear to low levels and providing satisfactory electrical properties under certain conditions.

The results of the first part of this program indicated that the recommended blend of 75 percent OS 124 and 25 percent MCS 210 consistently provided contact behavior in which hydrodynamic-lift effects did not seriously affect the electrical properties at about 19 C if the maximum velocity of the wiper did not exceed about 0.5 cm/sec. The velocity with which the brush moves over the armature in the ST-124M slip-ring capsule in its ultimate use is less than 0.1 cm/sec. Reportedly, the slip-ring contacts may be required to operate at temperatures ranging from 19 to 43 C. At 43 C, the wiper velocity of the simulated contacts in the first part of the study was able to approach 1.0 cm/sec without objectionable hydrodynamic lift.

The equipment used in these studies to evaluate the electrical performance of lubricated contacts imparted sinusoidal motion to one of the contact members for which the maximum speed was approximately 0.9 cm/sec. The stroke length was about 0.022 inch. Under these conditions, the electrical performance of contacts lubricated by the blend was satisfactory at 43 C but hydrodynamic lift separated the contacts at about 25 C or below. As a consequence, at certain positions along the wiped path, unacceptably high dynamic resistance was encountered.

As contact lift due to hydrodynamic effects decreases as the wiping velocity decreases, it was necessary to show that the blend can lubricate satisfactorily at low

*See interim report.

wiper speeds. Experiments with the maximum wiper speed of less than 0.1 cm/sec showed that the wear was not detectably different than it was for higher wiper speeds. However, on occasion at low wiper speeds, very sharp, short-duration (~2 to 3 milliseconds) resistance spikes with values in excess of 1/4 ohm were observed. Such spikes are undesirable from the standpoint of the transfer of high-frequency signals, but would not be of serious consequence for dc or low-frequency signals.

The objectives of the supplemental research described in this report were, then, (1) to obtain added confirmation of the suitability of the recommended blend by performing a statistically significant number of standardized experiments under conditions which included a maximum wiper speed of about 1 cm/sec, (2) to determine whether the effects of hydrodynamic lift can be reduced by proper wear-in procedures, (3) to obtain additional information about the cause of the short-duration resistance spikes observed when the wiper stroke was only 0.002 inch, and (4) to evaluate the ability of the 75 percent OS 124 and 25 percent MCS 210 blend to shield gold/Neyoro 28A contacts from vapors known to cause insulating deposits to form on unprotected contacts.

This report gives the results of experiments carried out to meet these objectives and restates the principal findings from the Interim Summary Report.

DESCRIPTION OF EXPERIMENTAL TECHNIQUES AND EQUIPMENT UTILIZED IN THE SUPPLEMENTAL EVALUATION STUDIES

All the equipment and techniques utilized in this supplemental study were developed during the performance of the original investigation and detailed descriptions are available in the interim report. Details pertinent to the evaluation of the specific results presented in this report are reviewed in the following three sections.

Fabrication and Preparation of Contacts

Each wiper was hand formed by bending 0.007-inch-diameter Neyoro 28A wire around a cylindrical mandrel. The finished wipers were in the form of a "U" with the radius of the curved portion being 1/8 inch. The other contact member was a flat plate approximately 0.040 inch thick by 0.25 x 0.4 inch on the sides, and was made up of several layers. The surface consisted of a thin, hard, layer of electrodeposited gold applied by the Autronex C* process. Under the hard exterior layer was a relatively thick ($\geq$ 10 mils) layer of softer gold deposited by the Temperex HD* process. A very thin nickel barrier was deposited between the heavy gold layer and the OFHC copper base material. Prior to application of the thin, hard-gold outer layer, 90 degree V-grooves were ground into the surface of the thick gold deposit. Each flat had seven such grooves running parallel with the longest edges. Details of the flats and methods of preparation are given in Appendix A of the interim report. As a further identification, the flats used were of the BMI-Type rather than the PS-Type mentioned in the Appendix cited.

*Sel Rex Corporation, Nutley, New Jersey.

Following normal solvent cleaning procedures, both contact members were immersed in a hot solution of chromic and sulfuric acids for 2 to 3 minutes, washed in tap water, immersed in boiling hydrogen-peroxide solution for 20 minutes, rinsed in boiling distilled water, and, finally, oven dried in air.

Description of Single-Contact-Pair Apparatus

Contact members used in this investigation were mounted inside chambers, called single-contact-pair chambers, in which was provided an atmosphere of prepurified nitrogen. All organic materials, except those introduced intentionally, were excluded from the environment of the contacts. Lubricant was applied to the flat contact by immersing one end of a Teflon rod in the lubricant and then touching the rod to the point where the wiper was to be positioned.

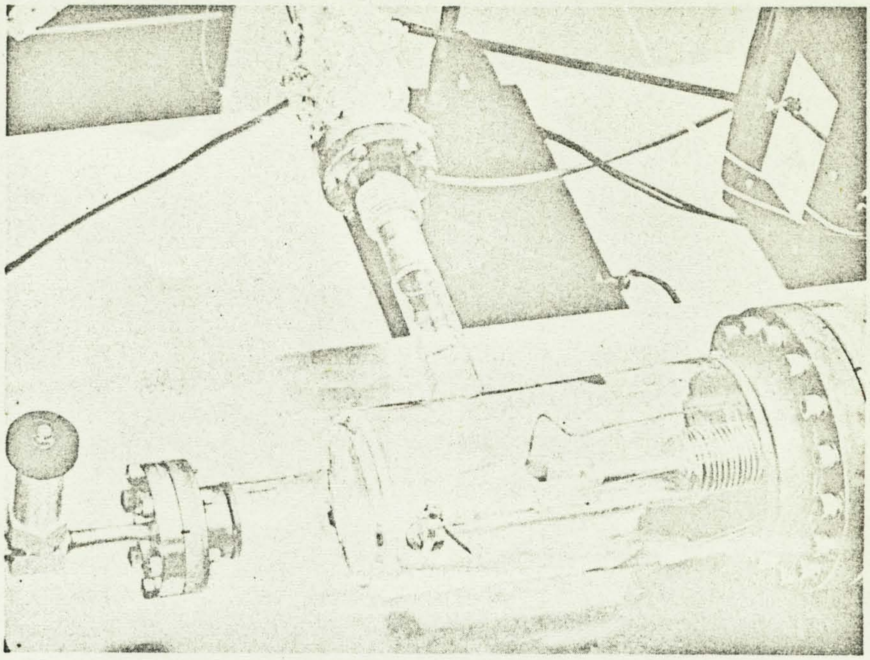
A photograph of one of the single-contact-pair units is shown in Figure 1. The contact flat is clamped at the end of a cylindrical rod which is supported by two ball bushings. It is driven sinusoidally at 5 cycles per second by an eccentric connected to the other end of the supporting rod. The wiper wire is mounted in a clamp in such a way that it can be lowered to just touch the flat contact. With the contacts just touching, a dead weight load ranging from 3.0 to 3.4 grams is applied to the wiper. Probes are applied at the points where the contacts touch their respective clamps. This means that a certain amount (constant throughout a given experiment) of the resistance measured and reported in these experiments is attributable to the inclusion of the bulk resistance of the contact members.

Description of the Dynamic-Resistance-Measuring Equipment

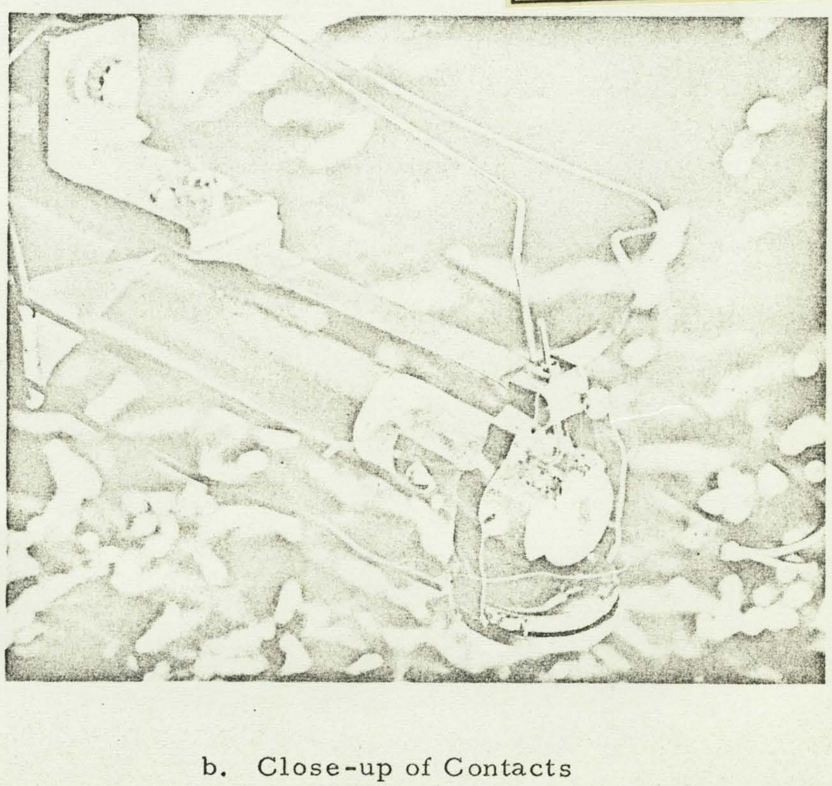
The circuit used to observe the dynamic resistance of single-contact pairs is shown schematically in Figure 2. A constant, alternating (20,000 Hz) current of 10 MA rms is passed through the contacts and the IR drop across the contacts is displayed on one of the channels of a two-channel oscilloscope. The sweep-rate of the oscilloscope is synchronized with the motion of the contacts so that slightly more than one wipe cycle is displayed. Thus, the envelope of the 20,000 Hz signal displayed on the oscilloscope varies in the same way as the resistance. A linear-motion potentiometer is coupled to the moving contact so that the signal from the potentiometer varies linearly with the position of the wiper, permitting the resistance values to be associated with known positions along the track.

RESULTS ON SUPPLEMENTAL STUDIES ON THE EFFECTIVE USE OF THE LUBRICANT BLEND

The research performed in the supplemental study covered in this report had four specific objectives. These four objectives, with the "standardized experiments" further



a. Chamber



b. Close-up of Contacts

FIGURE 1. PHOTOGRAPHS OF SINGLE-CONTACT-PAIR CHAMBER AND CONTACT ARRANGEMENT

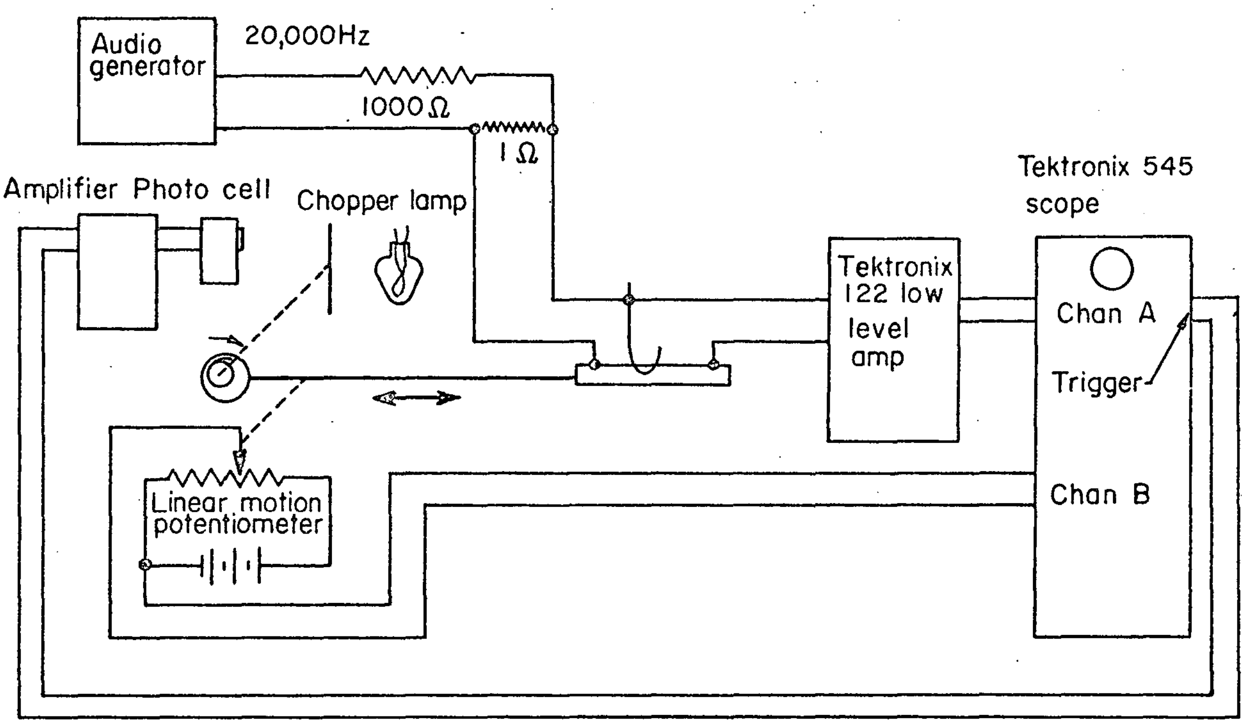


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FIGURE 2. SCHEMATIC REPRESENTATION OF CIRCUIT FOR MEASURING DYNAMIC CONTACT RESISTANCE

separated into room-temperature and 43-C studies, provide a convenient breakdown for presenting the experimental results. It must be recognized, however, that in many instances the results of a single experiment, or series of experiments, are pertinent to more than one of the four areas, and thus will appear in more than one section of the report.

The only way in which the precise dynamic-resistance characteristics of each lubricated contact-pair could be reported would be to reproduce all of the dynamic-resistance traces photographed from the oscilloscope face. For the number of experiments to be covered by this report, such a presentation would involve hundreds of such traces and would be impractical. Since the shapes of the dynamic resistance traces tend to be quite similar for contacts operating under the same conditions, a useful presentation can be made by including only a few dynamic-resistance traces to illustrate the various general types of curves and then reporting only numerical data taken from the individual traces for the various experiments.

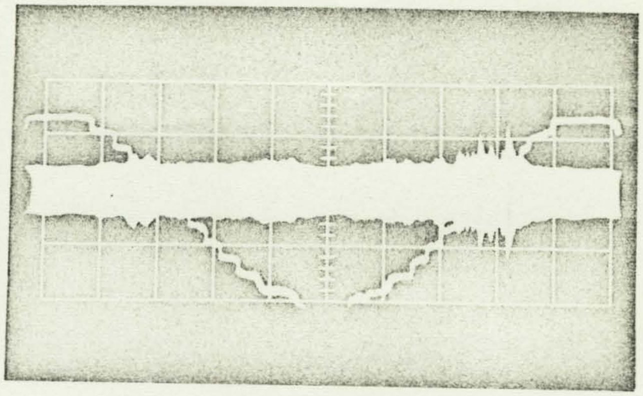
In general, the most sensitive indicator of the effects of the various parameters in these studies is the magnitude of the maximum dynamic resistance observed at any point on the trace (that is, at any point in the wiping path). As will be seen from the illustrative examples to be presented, the maximum resistance normally occurs only over a limited portion of the wiper path. In other words, the high resistance tends to occur more or less in the form of spikes superimposed upon a lower "average" resistance. The procedure adopted to characterize the dynamic resistance from a specific experiment for comparison with the results of other experiments is to list (1) the measured maximum value, no matter when it occurred during an experimental run (about 12 days, or 10^7 wipes) or how short its duration, and (2) the range of the minimum resistance found.

Care must be exercised in interpreting such data since the spread from the high- to the low-resistance values is not, in general, an indication of rms noise observed. In most traces, only a few short-duration spikes were observed. So the rms noise or the averaged integrated resistance would be extremely close to the minimum resistance values given.

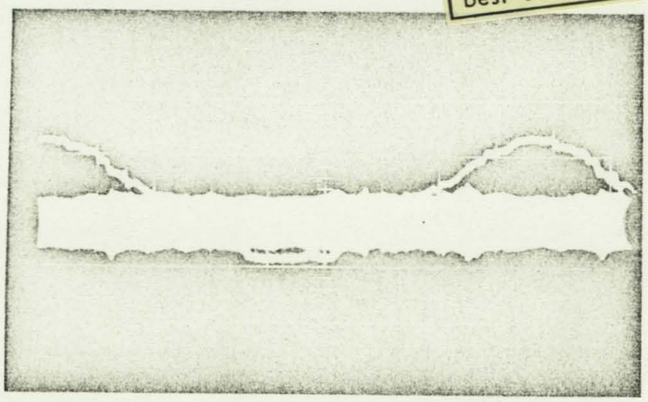
Dynamic Resistance Behavior of Contacts Operated Only at Room Temperature

Table 1 summarizes the dynamic resistance data for ten experiments carried out with the contacts at room temperature. Conditions for these experiments were standardized; that is, the length of the stroke was nominally 0.022 inch, the wiper completed five cycles per second, and the load was nominally 3 grams. Typical dynamic resistance traces from these experiments are shown in Figure 3.* Figure 3a shows a resistance trace which is representative of the cases in which comparatively large resistance spikes occur. It is clear that the spikes were considerably larger when the wiper was

*The low-frequency sine curve shown in the trace indicates the position of the wiper along its excursion. The extrema in this curve represents turn-around points of the wiper.



a. Experiment 158



b. Experiment 141

FIGURE 3. DYNAMIC RESISTANCE TRACES FOR CONTACTS LUBRICATED BY THE 75 PERCENT OS 124 AND 25 PERCENT MCS 210 BLEND OPERATING AT ROOM TEMPERATURE

Resistance scale: 1 major division equals 17.5 mΩ.

moving in one direction (the right half of the trace) than they were when the wiper was moving in the other direction. Such asymmetry is usually present when hydrodynamic-lift effects are occurring. It is due to mechanical instabilities in the contact supports. Figure 3b shows a trace in which the dynamic resistance varied by a ratio of less than 2:1 over the entire trace.

TABLE 1. DYNAMIC RESISTANCE VALUES FOR CONTACTS LUBRICATED BY THE 75 PERCENT OS 124 AND 25 PERCENT MCS 210 BLEND WHILE OPERATING AT ROOM TEMPERATURE

Experiment	Range of Minimum Dynamic Resistance Values, mΩ	Maximum Value of Dynamic Resistance, mΩ
139	15-1/2 - 17-1/2	31-1/2
141	15 - 17	24-1/2
142	13 - 15-1/2	25-1/2
144	14 - 17-1/2	70
147	13 - 16	21
148	14 - 17-1/2	73-1/2
149	16 - 21	140
153	11 - 12	210
158	14 - 16	70
163	12-1/2 - 16	700

If an arbitrary requirement of a ratio of maximum to minimum dynamic resistances of 2 is adopted as indicating satisfactory contact performance, four of the ten experiments would be acceptable. If a limit of about one-fourth ohm could be tolerated, all but one experiment would be acceptable. Of course, one must keep in mind that the data given is for a maximum wiper speed of 0.9 cm/sec. At about 0.5 cm/sec or less, no high-resistance spikes are seen. The higher maximum speed is used to show up more sensitively the dynamic effects.

The values of the maximum dynamic resistance for two room-temperature experiments are plotted as a function of hours of operation in Figure 4 to illustrate what appears to be a fairly general characteristic of the resistance behavior of contacts operating at room temperature, viz. a cyclical variation between high and low values of the maximum dynamic resistance. Maximum dynamic-resistance values appear to level off at reasonably low values near the ends of these two experiments, suggesting the possibility that, as a result of wear-in effects, the dynamic resistance for times longer than 284 hours might remain low. Another pair of contacts (Experiment 163) were operated over an extended period to investigate this possibility. The maximum dynamic resistance values obtained during Experiment 163 are plotted in Figure 5 as a function of hours of operation. Note that a change of symbols was made at 288 hours to signify that the contacts were stationary for two days at that point in operating time. The temperature throughout much of Experiment 163 was reduced below that of the room. The temperature at which each point was obtained is indicated on the plot. Because of the decrease in temperature, all of the dynamic-resistance values might be expected to be somewhat higher than they would have been at 23 C. The rate of wear might be expected to be reduced.

On the basis of this one experiment, it appears that the resistance was going through another cycle of strong hydrodynamic-lift effects and that the lower temperatures may have lowered the rate at which additional wear modified the contact behavior. Finally, it can be seen that returning the temperature to ~22 C produced, as expected, an immediate large drop in the effects of hydrodynamic lift upon the dynamic resistance.

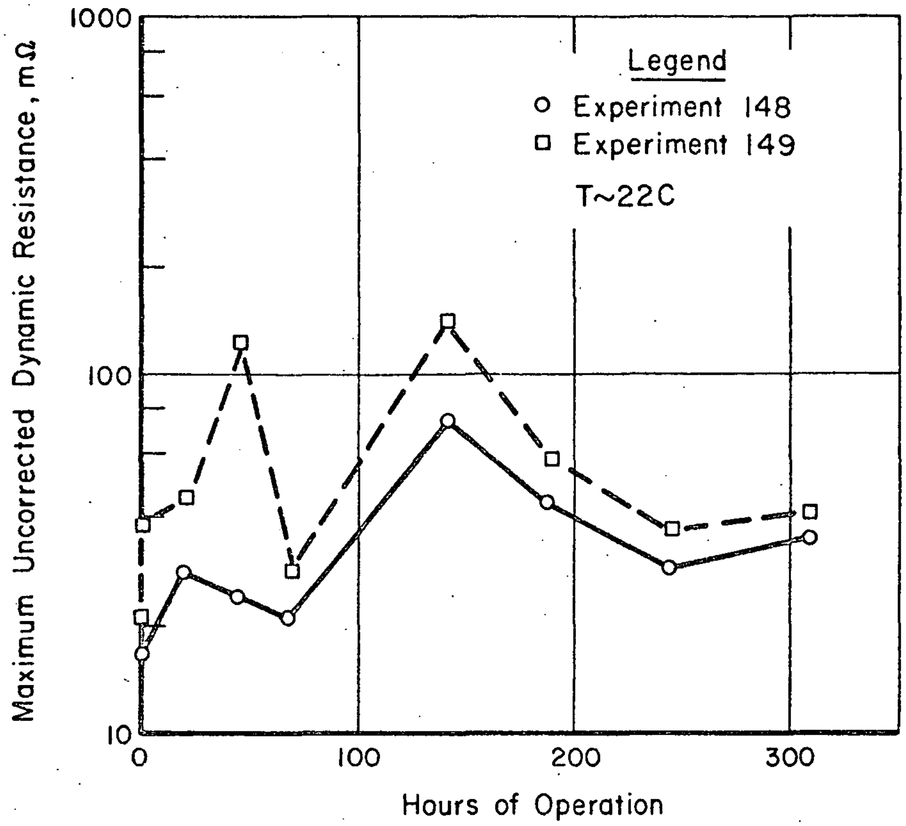


FIGURE 4. MAXIMUM VALUES OF THE DYNAMIC RESISTANCE OF GOLD/NEYORO 28A CONTACTS LUBRICATED BY A BLEND OF 75 PERCENT OS 124 AND 25 PERCENT MCS 210

Dynamic Resistance Behavior of Contacts Operated Only at Temperatures Near 43 C

A total of 11 contact pairs were operated at 43 C under standardized conditions for approximately 284 hours on each pair. Maximum and minimum dynamic resistance values for these 11 experiments are summarized in Table 2. The table shows a number of experiments where very high maximum dynamic resistance values are reported. Examples of a trace from an experiment where the dynamic resistance was highly uniform and of a case where very high dynamic resistance values were reported are shown in Figures 6a and 6b, respectively. The nature of the high resistance spikes is markedly different from those attributable to hydrodynamic lift. The spikes observed when the contacts are operating at about 43 C are of very short duration (usually ~2 to 3 milliseconds), reach their maximum value almost instantaneously then decrease

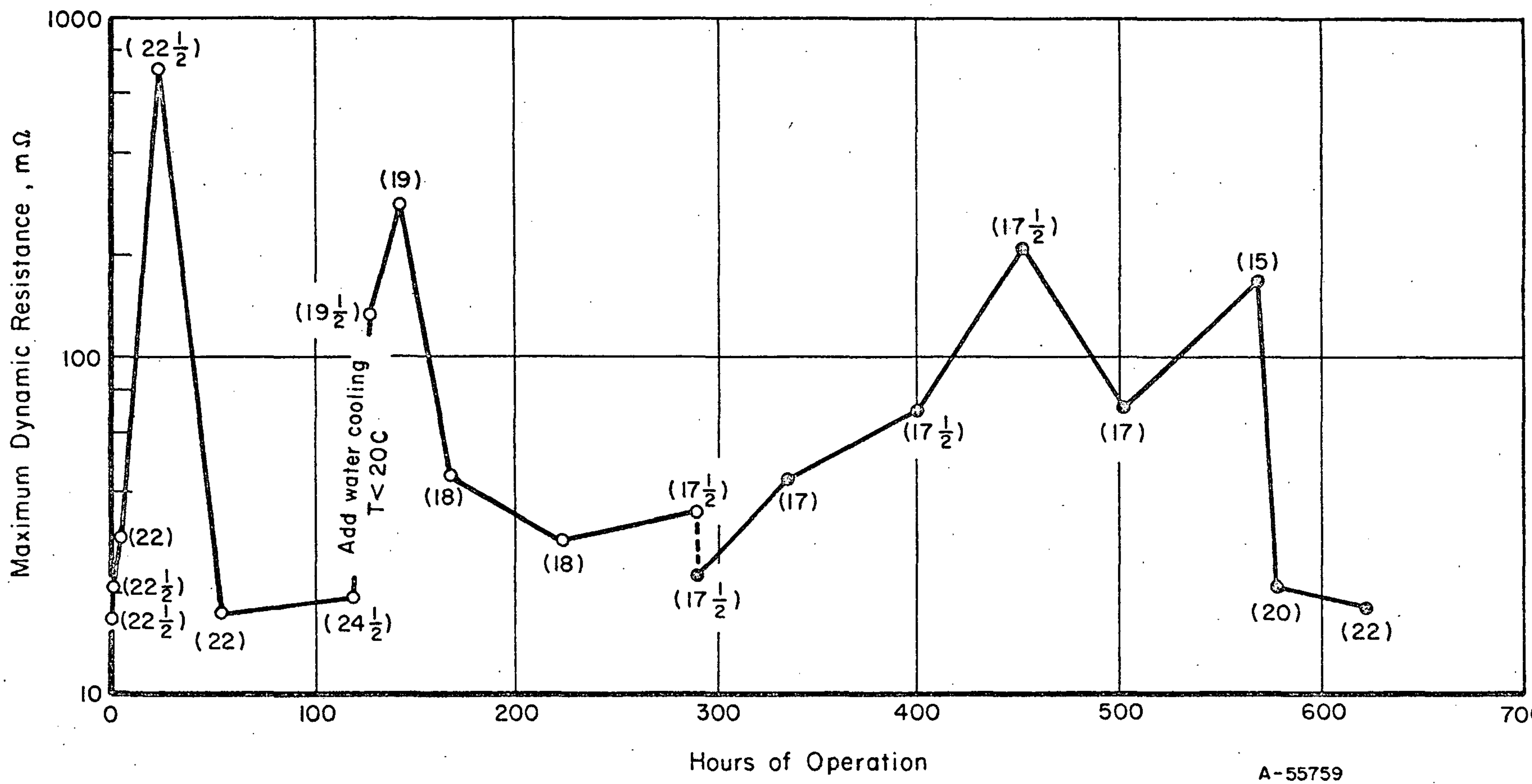
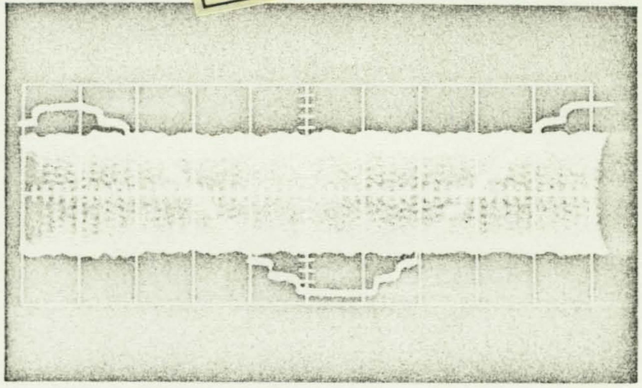


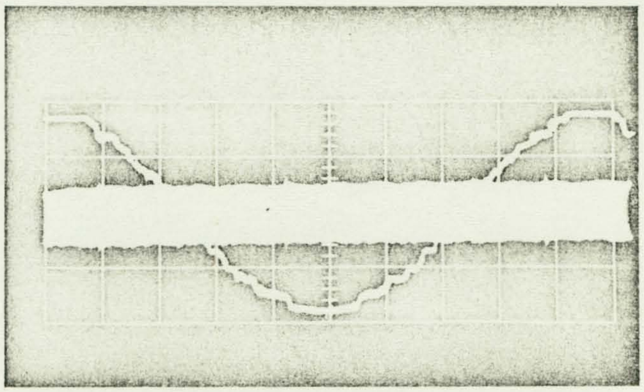
FIGURE 5. MAXIMUM VALUES OF THE DYNAMIC RESISTANCE OF GOLD/NEYORO 28A CONTACTS LUBRICATED BY A BLEND OF 75 PERCENT OS 124 AND 25 PERCENT MCS 210 DURING AN EXTENDED RUN

Contact temperatures, C, are indicated beside each data point.



a. Experiment 162

One major division = 7. 0 mΩ.



b. Experiment 161

One major division = 17. 5 mΩ.

FIGURE 6. TYPICAL DYNAMIC RESISTANCE TRACES SHOWING: (a) A CASE WHERE THE RESISTANCE IS HIGHLY UNIFORM OVER THE ENTIRE TRACK AND (b) A CASE WHERE HIGH-RESISTANCE SPIKES WERE OCCURRING

exponentially with time to the original low value, occur almost exclusively just before contact motion reverses or just after it has reversed, and rarely occur at exactly the same location along the track on consecutive wipes.

TABLE 2. DYNAMIC RESISTANCE VALUES FOR CONTACTS LUBRICATED BY THE 75 PERCENT OS 124 AND 25 PERCENT MCS 210 BLEND WHILE OPERATING AT TEMPERATURES NEAR 43 C

Experiment	Range of Minimum Dynamic Resistance Values, mΩ	Maximum Value of Dynamic Resistance, mΩ
143	17-1/2 - 21	700
145	14 - 16	21
146	13 - 14	35
154	12-1/2 - 14	18
155	14 - 17-1/2	1,700
156	15 - 28	560
157	12-1/2 - 14	16
159	13 - 14	70
160	15-1/2 - 17-1/2	70
161	16 - 18	1,700
162	14-1/2 - 16	18

Short-duration spikes (of the type observed for six of the 43 C experiments) apparently are caused by the wiper sticking to the flat briefly, then breaking free and sliding rapidly for a short time with an attendant resistance spike. That is, they are due to stick-slip behavior of the contacts. If the assignment of the cause is correct, then one should expect that reducing the lubricant temperature would reduce the tendency for short-duration spikes to occur (by increasing the lubricant viscosity). One would also expect that decreasing the dead-weight loading on the contacts should reduce this tendency. Finally, reducing the wiper speed at a given temperature should increase the tendency toward short-duration spikes. Experiments designed to test the validity of the stated hypotheses by determining whether the predicted behavior actually occurred are described next.

Experiments Designed to Reveal the Cause of Short-Duration Dynamic-Resistance Spikes

The results of one experiment (151) in which the temperature of the contacts was changed at various times during the run are shown in Figure 7. Note that for the first 18 hours (with the contact temperature about 43 C) short-duration spikes of about 100 milliohm were occurring. When the temperature was reduced to ~36 C, the spikes subsided for a period of about 1 day, after which the spikes returned (in one instance with greater magnitude than at 43 C) and remained until the temperature was reduced to 25 C. At 25 C no spikes were observed. Even when the contact temperature was eventually

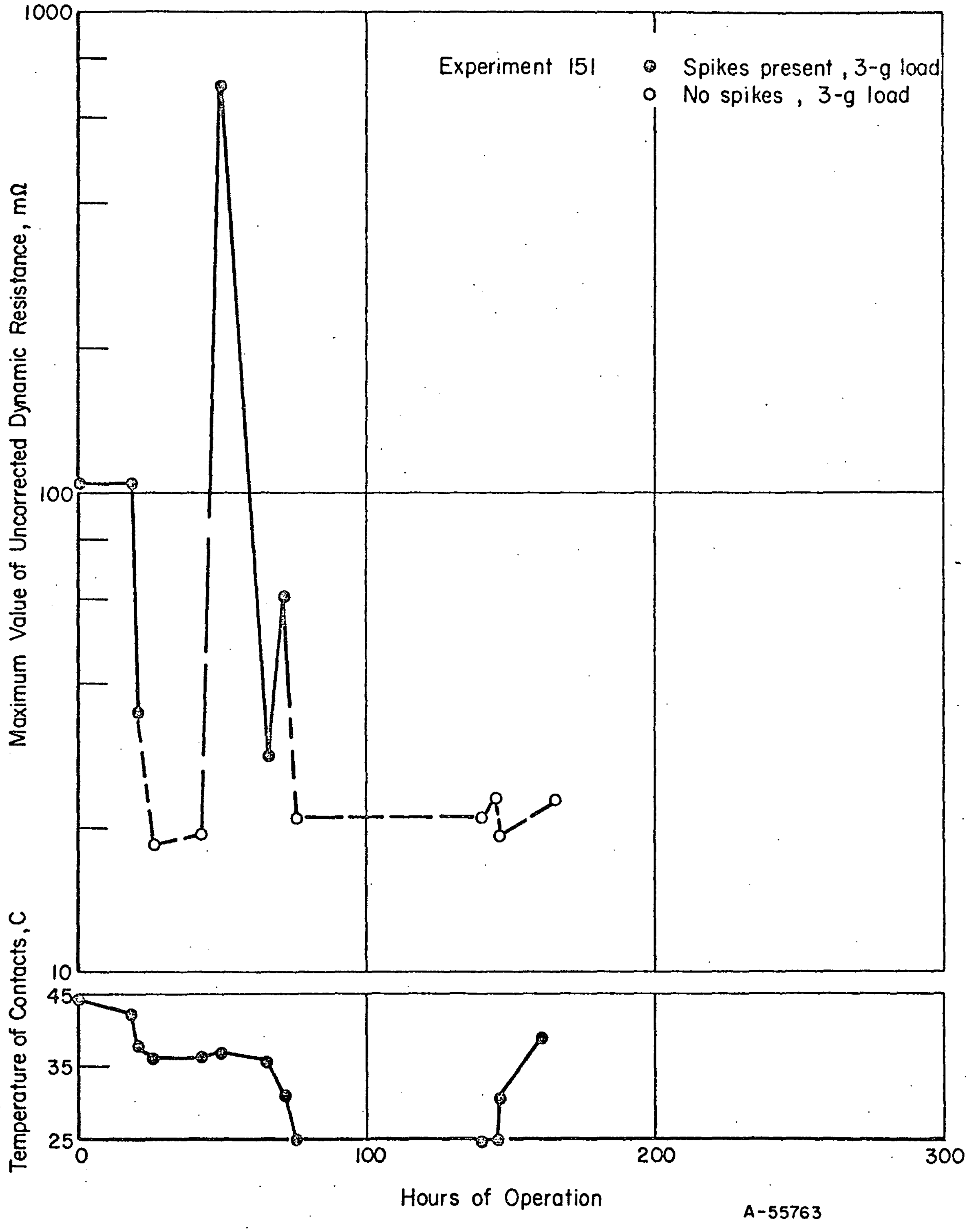


FIGURE 7. DYNAMIC RESISTANCE BEHAVIOR AND THERMAL HISTORY OF CONTACTS LUBRICATED BY A BLEND OF 75 PERCENT OS 124 AND 25 PERCENT MCS 210

returned to 40 C, the spikes did not reappear. The behavior observed in Experiment 151 was in general agreement with what had been expected on the basis of the hypothesized explanation for the short-duration spikes, but the return of spikes at ~36 C (the first time at this temperature) and failure of spikes to return at 40 C indicate that an important factor, other than lubricant viscosity, showed its effects during this experiment. Results of a number of experiments (to be presented in a later section) indicate that the other factor is a modification of the contacts by wear-in effects. The general results of Experiment 151 were verified by reducing the temperature to ~25 C for several of the experiments from among those with short-duration spikes listed in Table 2 after their regular 284-hour run was completed. In no case did short-duration spikes occur at the reduced temperature.

In another experiment (150) the contacts were operated at ~42 C for ~145 hours to establish that short-duration spikes were occurring. The load was reduced from 3.0 to 1.9 grams and the contacts were operated under reduced load for ~50 hours. Finally, the load was returned to 3 grams. The maximum dynamic-resistance values as a function of hours of operation for Experiment 150 are shown in Figure 8. Note that, as expected, a reduction in the load at 145 hours caused a reduction in the short-duration spikes. Again, however, it appears that changes that occurred on the surfaces of the contact members also exerted a considerable influence since the spikes did not return when the load was returned to 3 grams.

Changing the viscosity of the lubricant blend by changing the temperature quite clearly has an influence upon the tendency of a given contact pair to suffer stick-slip. Additional information concerning this effect was sought by performing an experiment in which the blend of lubricants was removed from contacts which were exhibiting stick-slip behavior and substituting the more viscous neat OS 124. The dynamic-resistance behavior of the contacts during this experiment is shown in Figure 9. Immediately following the change to the more viscous lubricant, the short-duration spikes underwent the expected reduction in magnitude. In fact, they were completely eliminated. After only a few hours (~16), however, spikes reappeared with considerably greater magnitude than the ones previously observed for the blend. The general behavior is that the spikes for the neat OS 124 are of greater magnitude than for the blend. The explanation for this behavior is not known. One possibility might be that the OS 124 film does not self-heal as well as that of the blend and thus does not return to the contact area soon enough after a wipe. At any rate, this one experiment suggests that even under conditions of stick-slip, there may be some advantage in using the blend of lubricants.

INVESTIGATIONS OF CONTROLLED WEAR-IN TO MODIFY THE EFFECTS OF HYDRODYNAMIC LIFT UPON THE DYNAMIC RESISTANCE

Figure 10 (taken from the Interim Summary Report) shows the maximum and minimum values of the dynamic resistance of plated-gold/Neyoro 28A contacts, lubricated by OS 124, at various contact temperatures. The sequence of measurements began at 30 C, increased to 48 C and remained there overnight, then decreased to 29 C. Clearly, the maximum resistance values were lower, especially at the lower temperatures, after the contacts operated overnight at 48 C. The difference on any given wipe between the maximum and minimum values of the dynamic resistance is primarily due to hydrodynamic lift of the wiper by the lubricating fluid.

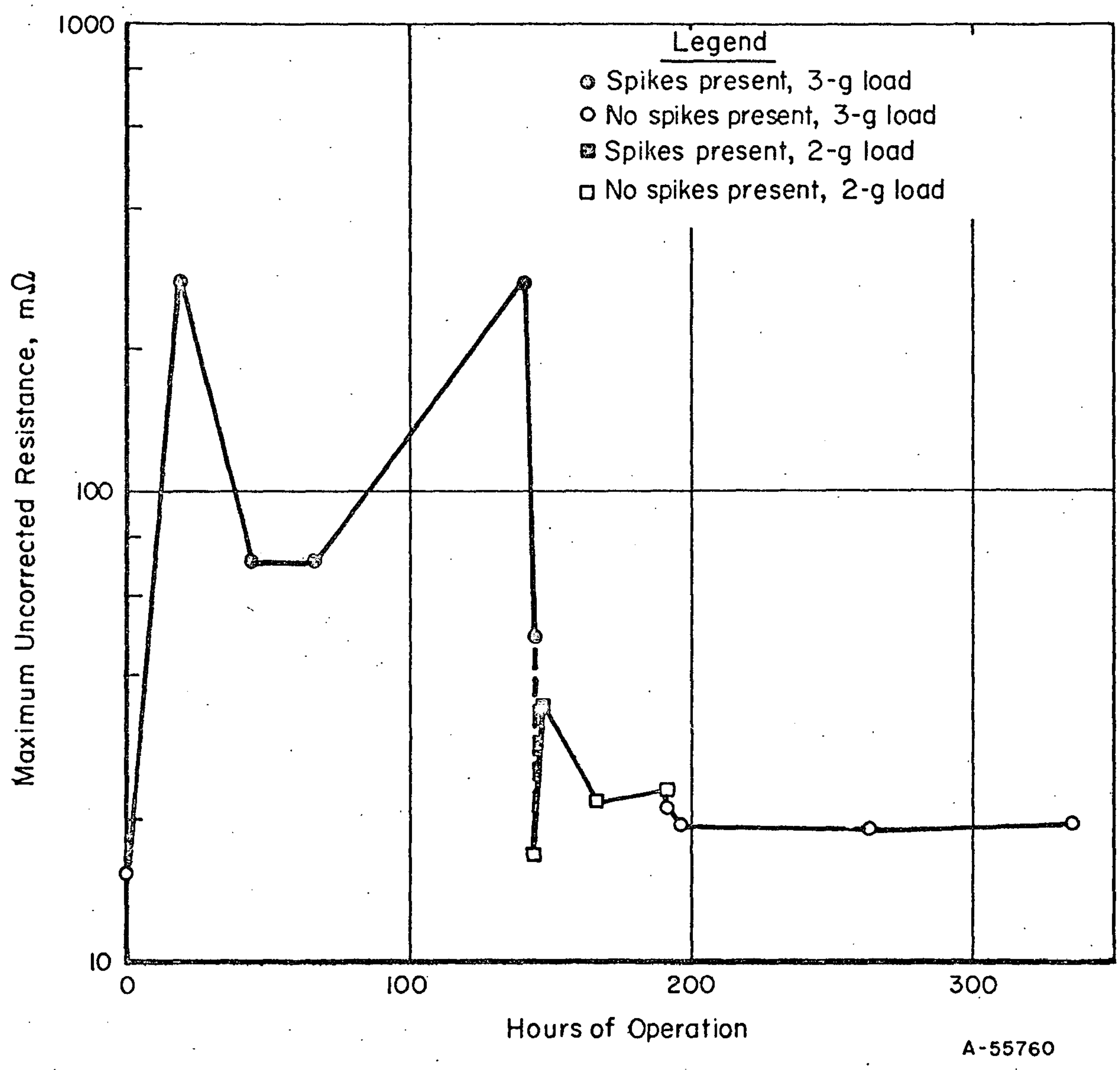


FIGURE 8. DYNAMIC RESISTANCE BEHAVIOR OF CONTACTS LUBRICATED BY A BLEND OF 75 PERCENT OS 124 AND 25 PERCENT MCS 210 FOR DIFFERENT APPLIED LOADS

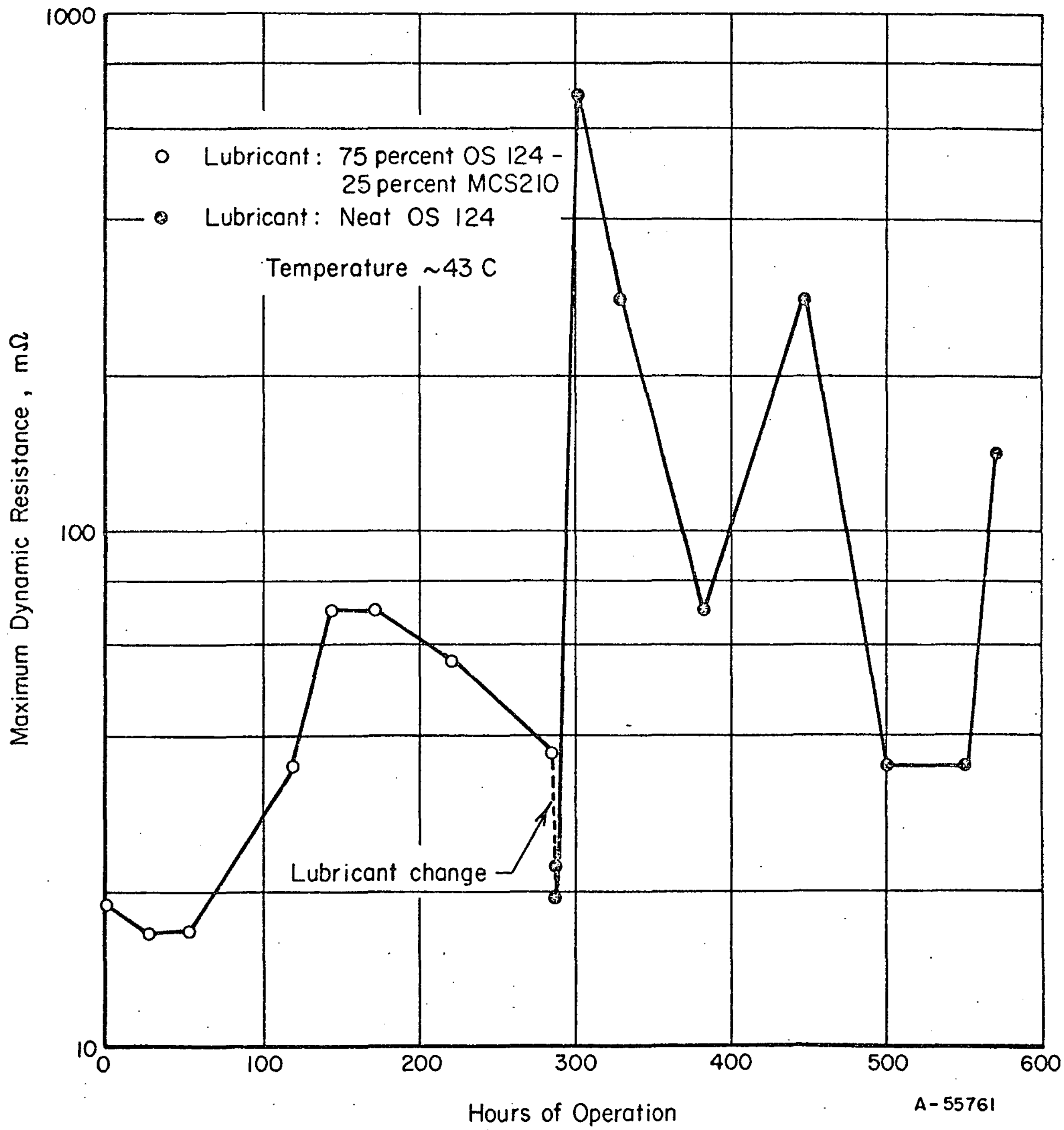


FIGURE 9. MAXIMUM DYNAMIC RESISTANCE FOR CONTACTS LUBRICATED FIRST BY A BLEND OF 75 PERCENT OS 124 AND 25 PERCENT MCS 210, THEN LATER BY NEAT OS 124

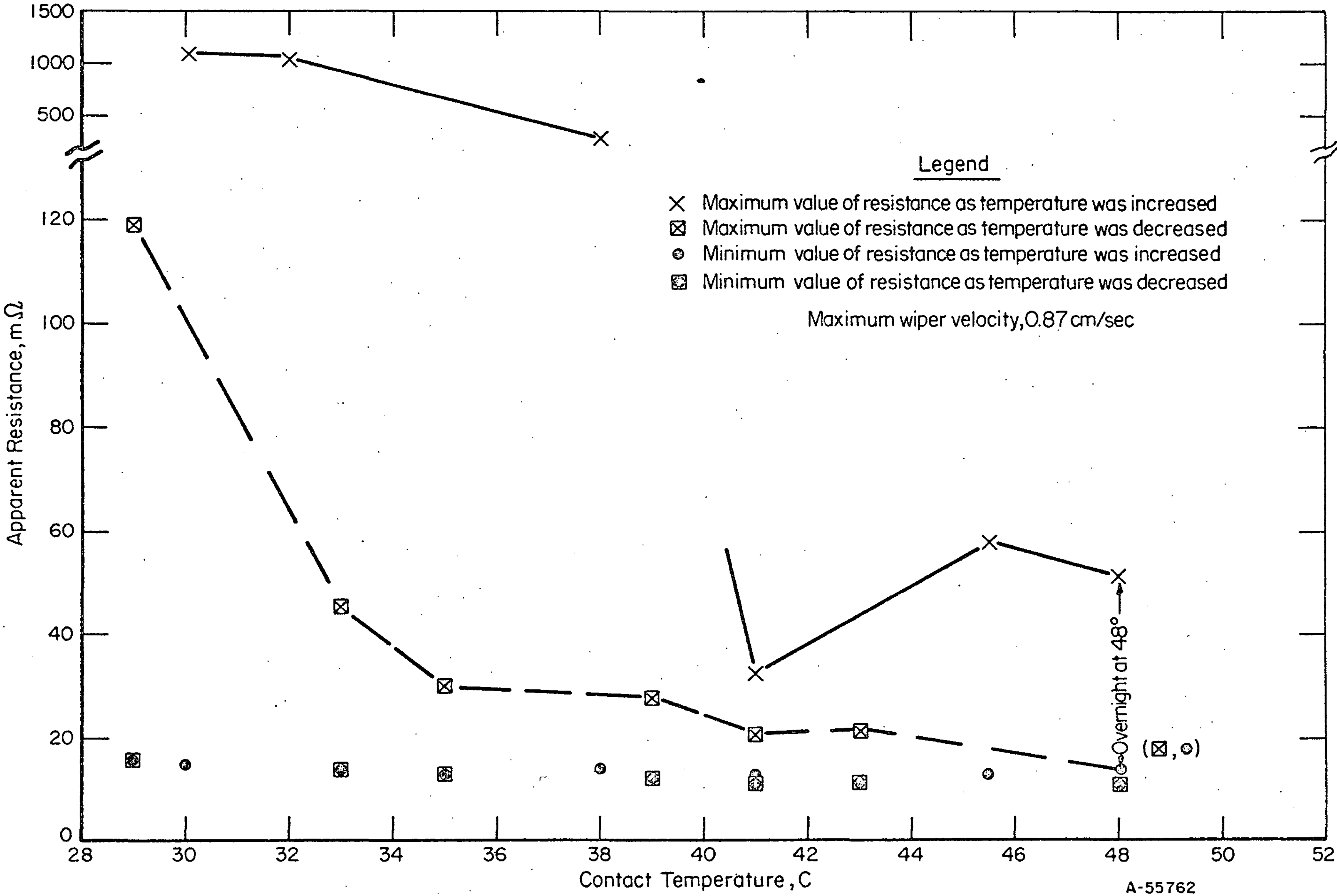


FIGURE 10. DYNAMIC ELECTRICAL RESISTANCE OF CONTACTS LUBRICATED BY OS 124 AS A FUNCTION OF CONTACT TEMPERATURE

A possible explanation for the observed change in maximum dynamic resistance values after operating the contacts at 48 C is that the lubricant (OS 124) underwent some change while at this temperature. The fact that contacts lubricated by other liquids exhibited very similar behavior made this explanation seem improbable. Eventually it was shown, for several different contact pairs, that operating the contacts at temperatures above 40 C did not produce the same effect if they had previously operated for prolonged periods at room temperature. These results tended to verify the opinion, held from the outset, that modification of the surfaces of the contacts due possibly to some optimum amount of metal-to-metal contact during the period when the contacts were at the higher temperature lead to less severe hydrodynamic-lift effects. This supposition suggested the possibility that improved room-temperature dynamic resistance characteristics might be achieved if an appropriate initial elevated temperature run-in could be established. Several experiments were performed in the present study in an attempt to identify such a procedure.

The data listed in Table 1 can serve as a basis for comparison in evaluating the effects of run-in techniques, since these data represent the results for a number of experiments in which the temperature remained at room temperature. As pointed out in an earlier section, six out of ten of these experiments exhibited, at least part of the time, moderately severe effects of hydrodynamic lift in the dynamic resistance. In Table 3 the equivalent data are given for contact pairs that were operated at 43 C for various lengths of time prior to operation at room temperature. Also listed is one experiment in which the contacts were operated for 3 hours at 34 C prior to room-temperature operation. With the exception of Experiment 133, the contacts remained at room temperature once they were cooled. In every experiment, contact motion was interrupted during the periods when the temperature was being changed. Motion occurred only at the temperatures listed.

TABLE 3. DYNAMIC-RESISTANCE VALUES FOR CONTACTS OPERATING AT ROOM TEMPERATURE AFTER PREVIOUS WEAR-IN AT HIGHER TEMPERATURE

Experiment	Preconditioning Treatment	Time at Room Temperature, hours	Maximum Dynamic Resistance During Time at Room Temperature, mΩ
132	16 Hours at 43 C	266	28
133 (A)	1 Hour at 43 C	19	950
133 (B)	(A) Above Plus 4 Hours at 43 C	40	1400
133 (C)	(A) and (B) Above Plus 8 Hours at 43 C	32	1500
136	3 Hours at 43 C	281	21
137	3 Hours at 43 C	283	28
138	3 Hours at 34 C	192	24

Data of Table 3 show that the dynamic-resistance behavior was highly satisfactory for every experiment in which the contacts were preconditioned for a period of at least 3 hours. Data presented in Table 1 show that equally satisfactory dynamic-resistance behavior was obtained for three out of ten experiments in which the contacts were not preconditioned. On the basis of the expectation that less than one out of two unconditioned contact pairs would provide satisfactory room-temperature dynamic-resistance behavior, it is reasonable to attribute the perfect record for the contacts preconditioned for 3 hours at 43 C to the effects of wear-in. The results for the lone contact pair preconditioned at 34 C probably indicate that even this procedure was helpful in minimizing the effects of hydrodymanic lift. In this case, however, there is a significant chance that the dynamic resistance would have been acceptable without preconditioning.

Experiment 133 (Table 3) demonstrated that preconditioning for 1 hour at 43 C is not sufficient to insure that the effects of hydrodynamic lift will be small at room temperature. It also suggests that attempts to achieve the desired contact surfaces following operation for about a day at room temperature are not likely to succeed. Certain of the contact pairs listed in Table 1 that exhibited high dynamic resistance at room temperature were heated to 43 C and operated for 3 hours. In every case, high dynamic-resistance spikes were observed when the contacts were again cooled to room temperature. On the other hand, contacts that had operated for 284 hours at 43 C reached acceptably low dynamic resistance very rapidly when they were subsequently operated at room temperature.

In summary, the status of the wear-in effects on contacts lubricated with the blend of lubricants as they are now understood is: (1) wiping the contacts at 43 C with a maximum wiper speed of about 1 cm/sec for approximately 10^5 wipes conditions the contact surfaces in such a way that hydrodynamic lift does not severely affect the dynamic resistance during subsequent operations at room temperature, (2) wiping the contacts at room temperature can lead to surface changes that are not optimized by subsequent operation at 43 C, and (3) prolonged wear at 43 C does not appreciably degrade the subsequent dynamic-resistance behavior at room temperature.

RESULTS OF EXPERIMENTS WITH THE WIPER RESTRICTED TO VERY SMALL EXCURSIONS

Results of studies with hydrodynamic-lift effects (see interim report) indicated that contacts operating at wiper speeds lower than the standardized value of ~0.9 cm/sec exhibited different dynamic-resistance characteristics, and quite possibly different wear behavior. No effort was made to investigate higher wiper speeds because the electrical contact behavior would undoubtedly have been unsatisfactory and the speed of 0.9 cm/sec was higher than those encountered in actual slip rings of the type of interest to this program. Much of the time actual slip-ring wipers would be hunting around a center position on the rings at low wiping speeds. As a consequence of this, the performance of experimental contacts lubricated with the most promising lubricants were evaluated in short-stroke, low-speed service.

Two single-contact-pair units were modified to provide a stroke of only 0.002 inch. Since the same wipe frequency was retained, the maximum wiper speed for the short-stroke experiments was about 0.08 cm/sec. For the work reported in the Interim Summary Report, one contact pair was lubricated with OS 124 and one pair with the

75 percent OS 124 and 25 percent MCS 210 blend. The thermal conditions for both experiments were: 2 days at room temperature, followed by 14 days at 43 C, followed finally by 1 day at room temperature. From the beginning of the experiment with the blend as lubricant, there were periods in which very short duration spikes were observed, indicating relatively high instantaneous dynamic-resistance values.* For contacts lubricated with OS 124, short-duration spikes were not encountered until the temperature reached 43 C. They persisted when the temperature was returned to room temperature. Post-run examination of the contacts from the first short-stroke experiments revealed that contact wear was not detectably different than that observed for normal-stroke (0.022 inch) experiments. An unexpected result was that the wear scars were much longer (from 0.010 to 0.020 inch) than the stroke length.

The cause of the short-duration spikes became clear during the extensive study described previously in the section concerned with short-duration resistance spikes. Before this information was available it was considered important to seek additional information concerning the expected behavior of contacts operating under short-stroke conditions. Consequently during the period covered by the present report, four additional short-stroke experiments were performed. Two experiments were run with the contacts at 43 C throughout. Again, one contact pair was lubricated by the blend and the other by OS 124. The remaining two experiments were run with the contacts at room temperature throughout; both of these utilized the lubricant blend.

Both contact pairs operated at 43 C exhibited the short-duration spikes of high dynamic resistance. One of the contact pairs operated at room temperature completed 284 hours without spikes being observed, while spikes were observed throughout the other run. Again microscopic examination of the contacts following the experiments did not reveal unusual wear, and again the scars on the contact flats were much longer than the stroke length.

One possible explanation for the short-duration spikes is that they result from stick-slip behavior which occurs when the effective load borne by the lubricant film falls below some critical value.

There are significant differences between the geometrical configuration of the contacts employed in this study and those found in actual slip rings. These differences, along with the possibility of differences in mechanical stability, need to be considered in attempting to anticipate how the proposed lubricant will perform in actual slip-ring capsules. In the next section an attempt is made to describe briefly a working hypothesis that provides a general description of the electrical behavior of lubricated contacts and to consider how the behavior of actual slip rings might differ from the behavior of those used for this study.

*Identical spikes have been described and illustrated in this report in the section dealing with contacts operated at temperatures near 43 C. But such spikes were first encountered in short-stroke experiments.

HYPOTHESES RELATING TO ELECTRICAL BEHAVIOR OF LUBRICATED CONTACTS AND TO EXPERIMENTAL VERSUS ACTUAL CONTACTS

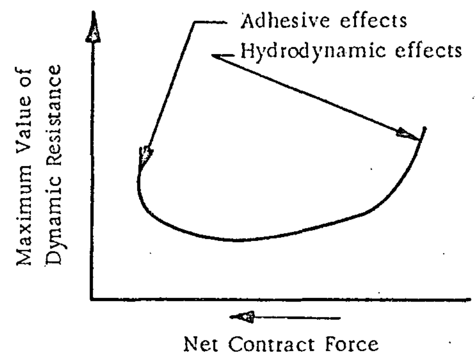
Low contact resistance can be achieved only when initimate metal-to-metal (asperity) contact occurs.* When any fluid is placed between two solid surfaces which are in motion relative to one another, a pressure is developed in the fluid which tries to separate the two surfaces. The magnitude of the force depends upon the topographics of the surfaces, the viscosity of the fluid, and the speed of the relative motion. If these factors are held constant except the speed of motion, the force trying to separate the two surfaces becomes greater as the relative speed increases, or conversely, the force decreases as the speed decreases. Thus, for preloaded contacts, the net load actually transmitted through metal-to-metal contact can vary from its static (actual preload) value to zero. If the relative displacement of one surface with respect to the other is sinusoidal, the net contact force may vary over a considerable range during a single wipe cycle.

Under the more usual circumstances, surfaces are covered by sorbed films of some sort or another. If the two similar surfaces are pressed together, the films of foreign substances prevent the surfaces from adhering to each other. If the pressure is increased, however, the film eventually may rupture so that adherence may occur. In the case of lubricated contacts, the relative motion between them may become low enough that the preload force ruptures the lubricant film and produces adherence between the contacts. If more and more force is applied parallel with the macroscopic surfaces, a value will be reached such that the contacts will eventually separate and relative motion between them will resume. If one of the contacts is distorted during the period when it is sticking to the other contact member, it may slide rapidly back into position as the stored energy is released.

The results of this program would suggest that the major factor in determining contact performance is the net contact force. If the net force is too great, adhesive effects such as the stick-slip just described can occur, leading to short-duration, high-resistance spikes. If the net force is too small, the contacts may separate and extremely high resistance values can occur. In addition to the preloading, the net force depends upon the viscosity of the lubricant, the shape and surface texture of the contacts, and the contact velocity.

On the basis of this discussion, one would expect that a plot of the maximum values of the dynamic resistance for lubricated contacts as a function of net contact force would have the general shape sketched on the next page. If other variables are held constant, the net contact force, while not known, can be caused to vary by changing the wiper speed. The results of an experiment where this was done are shown in Figure 11. The lubricant was the 75 percent OS 124 and 25 percent MCS 210 blend, and the contact temperature was 23 C. The data shown were obtained after the contacts had previously been operated for 23 hours at room temperature. The dynamic resistance of these particular contacts followed the pattern shown in Figure 4. At the 23-hour point, the maximum value of the dynamic resistance was reasonably high under standard conditions.

*The use of conductive liquids is precluded for slip rings by the necessity to isolate adjacent electrical circuits.



As seen in Figure 11, the actual behavior shows the features predicted. If it is assumed that the lifting force is proportional to wiper speed (see Appendix C of the interim report), the shape of the assumed universal curve would look like the one in Figure 11. At the low speeds, adhesive effects on the contact resistance are evident. As the speed increases, a range is passed in which the dynamic resistance is almost as small as the static resistance. As the speed is increased still further, dynamic resistances increase owing to hydrodynamic effects. As has been pointed out, with the type of measurements used in this program, adhesive effects and hydrodynamic effects can be distinguished easily.

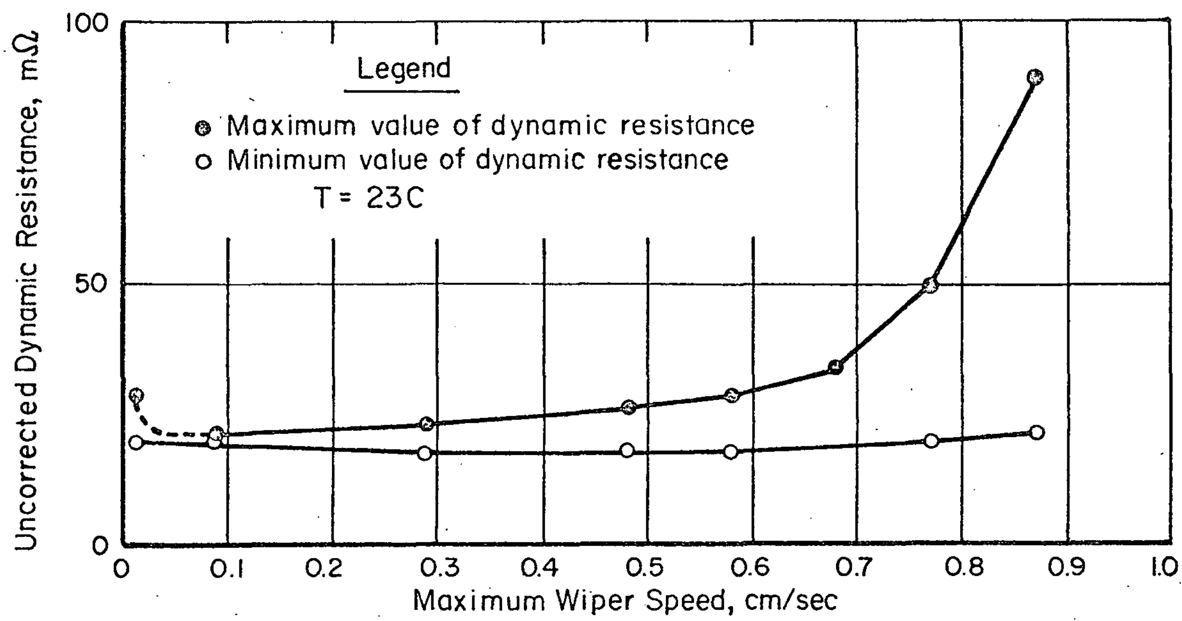


FIGURE 11. MAXIMUM AND MINIMUM DYNAMIC RESISTANCES AS A FUNCTION OF MAXIMUM CONTACT SPEED FOR GOLD/NEYORO 28A CONTACTS WITH 75 PERCENT OS 124 AND 25 PERCENT MCS 210 LUBRICANT

The speed at which adhesive effects occur may be a function of the wiper-stroke length. For example, in the short-stroke experiments, high-resistance spikes occurred at maximum wiping speeds near 0.08 cm/sec. Such spikes did not occur in the normal-stroke experiment (Figure 11) until the speed had been reduced to about 0.02 cm/sec.

The difference may be associated with the length of time the wiper spends near the turn-around points. At what wiper speed short-duration spikes occur in the actual slip-ring capsule is open to some question. But short-duration spikes must be expected for some low speed for any contact lubricant, even for greases. Ultimately in the static case (no relative motion), the lubricant will be pushed away and adhesive effects will occur.

These data (Figure 11) also serve to point out again that the dynamic resistances recorded for the lubrication repeatability studies discussed in a prior section of this report were obtained at a wiper speed higher than is to be encountered with the actual slip-ring capsule. All lubricated contacts became satisfactory from a slightly lower wiper speed down to extremely low wiper speeds where adhesive effects occur, as just explained.

The contacts in the single-contact chambers in this investigation are mounted on relatively long (~7 inch) horizontal arms. These arms, and the wiper support arm in particular, are most prone to experience vertical vibrational movement. Any such vibrations could, and undoubtedly did, enhance the tendency for contacts to exhibit high dynamic-resistance spikes. The brush assemblies of an actual slip ring are much less likely to respond to vibrations.

The wipers utilized in the experiments described in this report, 0.007-inch-diameter Neyoro 28A, were bent into the shape of a "U". The wiper was clamped at each leg in a manner that allowed the semicircular contact surface to extend about 3/8-inch below the clamp. Undoubtedly, the flexible wiper bends slightly as the frictional forces become appreciable. With such bending, the rounded portion of the wiper might roll in the groove of the flat instead of experiencing the desired sliding motion. Thus, it may be that the unexpectedly long wear scars resulted from a rolling action of the wiper in the groove of the flat. The geometry of wiper-ring relationships of actual slip rings would make it very difficult for the wiper to roll in the groove of the ring. Also, the brush would be far less susceptible to motion resulting from instantaneous seizing between the contacts, since in an actual slip-ring capsule, the force would be essentially along the longitudinal axis of the wire rather than normal to it. In the original lubrication studies described in the interim report, the wipers were formed from 0.030-inch-diameter wire. With this somewhat stronger wiper, the short-duration type of dynamic-resistance spikes were never observed, even at lubricant temperatures of 50 C. Such spikes were observed with unlubricated contacts which utilized 0.030-inch-diameter wire for the wiper, however. Thus it is believed, as one would desire, that the conditions under which the present study was conducted would tend to produce more severe variations in the dynamic-resistance values of lubricated contacts than might be expected in actual slip-ring capsules.

An indication that the conditions imposed upon the contacts in this study are such that they intensify dynamic-resistance variations is given in Figure 12. This figure shows a dynamic-resistance trace of a contact pair operating without lubrication at room temperature. Two wipe cycles are shown on the trace. Note that, as pointed out in earlier sections of this report, the area in which stick-slip is most severe is at one of the turn-around points. Stick-slip effects for one direction of wiper travel is much greater than for the other. These contacts were operating under essentially the same degree of lubrication as that under which actual slip rings normally provide satisfactory performance.

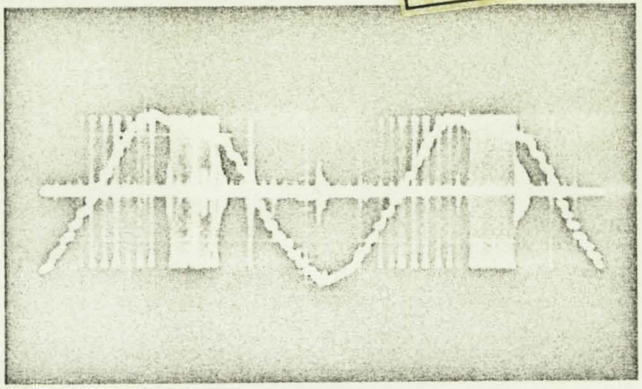


FIGURE 12. DYNAMIC RESISTANCE TRACE (TWO WIPE CYCLES) FOR UNLUBRICATED GOLD/NEYORO 28A CONTACTS

Resistance scale: one major division equals 350 mΩ.

EVALUATION OF THE LUBRICANT BLEND FOR SHIELDING CONTACTS FROM DEPOSIT-FORMING ORGANIC VAPORS

A large portion of the total program was concerned with the degree to which the off-gas products of various organic materials contributed to the formation of insulating deposits on simulated slip-ring contacts. Results of the first part of the program indicated that to eliminate contact deposits changes are required in the materials and processes used to fabricate the slip-ring capsule. They also showed that the atmosphere within a "green" platform contains numerous species of organic vapors, some of which are known to cause harmful deposits on plated-gold/Neyoro 28A contacts. In view of these facts, an extremely valuable attribute of the lubricant used on the contacts would be its ability to shield the contacts from potential deposit-forming vapors. With adequate shielding, changes in the slip-ring capsule might not be needed, and, very importantly, an effort to "clean up" the whole platform atmosphere may likewise not be required. Several experiments were conducted to determine whether the recommended lubricant blend might provide such shielding to a significant degree.

In selecting the source of the organic vapors, the facts that (1) the analysis of the off-gas materials from a green platform revealed a sizeable amount of tetrachloroethylene, (2) analysis of Kester AP-20 Rosin Residue Remover* indicated that it was primarily tetrachoroethylene, and (3) the finding that exposure of gold/Neyoro 28A Contacts to Kester AP-20 vapors caused deposits that increased the resistance all lead to the selection of Kester AP-20 as the source of the organic vapors for the shielding studies.

One of the gages that might be used to evaluate the ability (or lack of it) of the blend to shield the contacts from AP-20 vapors is the magnitude of the dynamic contact resistance. This gage involves some uncertainty since hydrodynamic-lift effects might not be separable from deposit effects, especially at room temperature. Earlier observations in many deposit-formation studies, however, indicate that the highest resistances

*Kester Solder Company, Chicago, Illinois.

due to insulating deposits tend to occur very near the turn-around points, while the lubrication studies showed that the effects of hydrodynamic lift are minimal at the turn-around points. Thus, a comparison of the dynamic-resistance values at the turn-around points for lubricated contacts exposed to AP-20 vapors with those of unexposed contacts should provide a reasonably accurate indication of any effect attributable to the presence of the AP-20 vapors. The main reason for selecting dynamic-resistance values over static values was that dynamic values could be obtained in a much shorter time. Another factor considered was that, in previous deposit studies, vapors sometimes accumulated on the contacts during the inoperative period used for the static-resistance measurements to such an extent that high contact resistances attributable soley to the condensed vapors were observed.

Dynamic-resistance values taken at the turn-around points for contacts lubricated by the blend and simultaneously exposed to vapors from Kester AP-20 are shown in Figure 13. When the resistances were not the same at both ends of the wipe, the higher value was plotted. For two experiments the contacts were heated to 43 C. The contacts were at room temperature for the other experiment. One of the 43-C experiments utilized a 0.030-inch-diameter wiper of the type used in the earliest studies. The other wipers were formed from 0.007-inch-diameter wire. The 0.030-inch-diameter wiper was loaded with 11 grams. Dynamic-resistance traces obtained near the end of the runs are shown in Figure 14 for 43-C and room-temperature runs. The 43-C run is the one that utilized

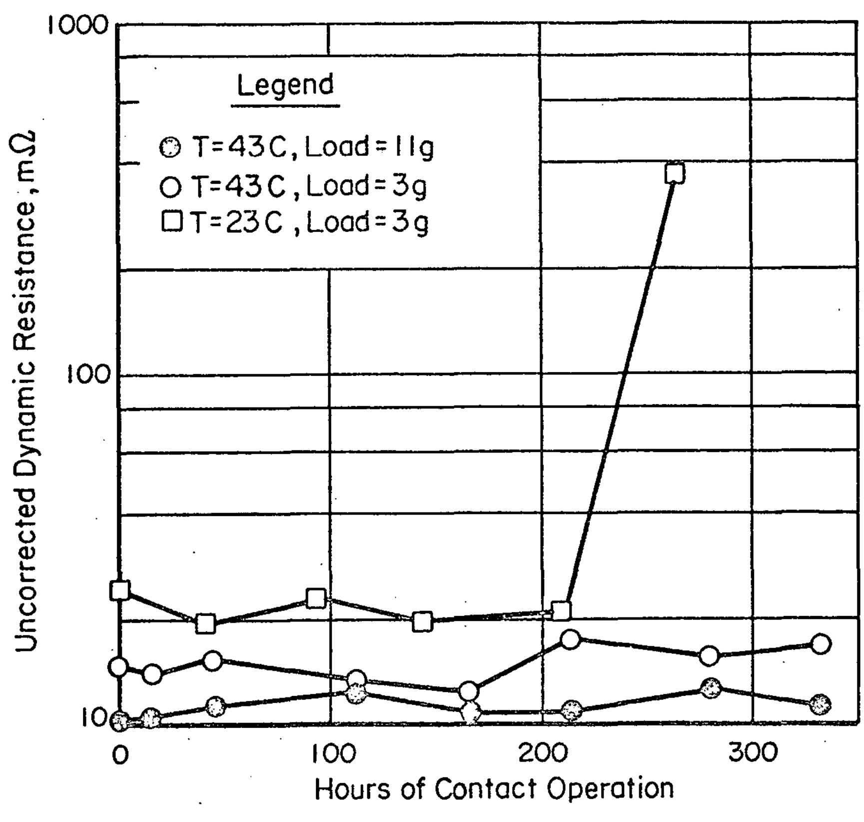
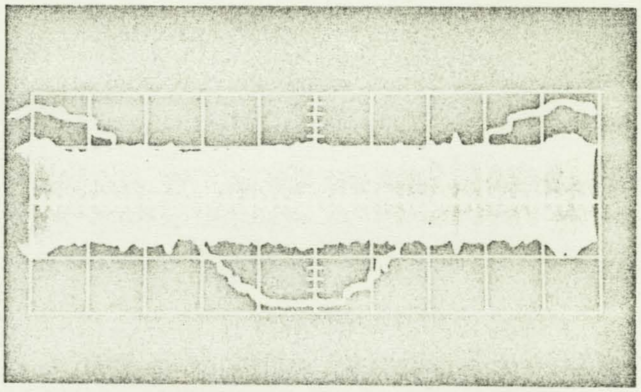
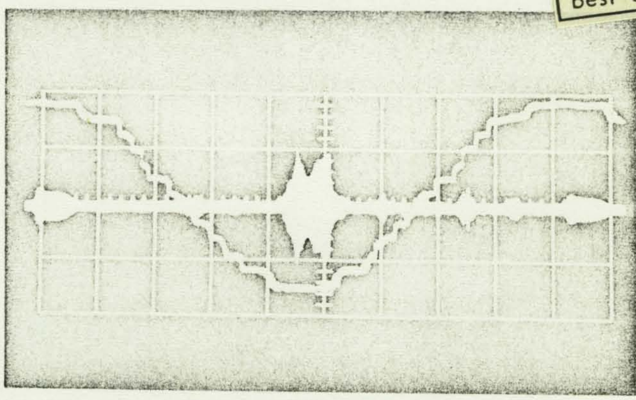


FIGURE 13. DYNAMIC-RESISTANCE VALUES AT TURN-AROUND POINTS FOR CONTACTS LUBRICATED BY 75 PERCENT OS 124-25 PERCENT MCS 210 AND EXPOSED TO VAPORS FROM KESTER AP-20



a. 280 Hours at 43 C

One major division = 7 mΩ.



b. 260 Hours at 24 C

One major division = 175 mΩ.

FIGURE 14. DYNAMIC RESISTANCE TRACES FOR CONTACTS LUBRICATED BY 75 PERCENT OS 124 AND 25 PERCENT MCS 210 AND EXPOSED TO VAPORS FROM KESTER AP-20

the 0.007-inch-diameter wiper. While not drastically so, the resistances at the turn-around points became larger than the average dynamic resistance for the 43-C runs. The final value for the room-temperature run is extremely large. By comparison, the dynamic resistance of unlubricated contacts exposed to vapors from AP-20 reached values of about 30 milliohms after only 8 hours of room-temperature operation.

The presence of the 75 percent OS 124-25 percent MCS 210 blend on the contacts obviously reduced the known tendency of vapors from Kester AP-20 to cause increased resistance on sliding plated-gold/Neyoro 28A contacts. However, visual examination of the lubricated contacts that were exposed to vapors from AP-20 revealed the presence (even for the contacts operated at 43 C) of dark deposits on the contacts. Photographs of the 0.030-inch-diameter wiper and its companion flat (from one of the 43-C runs) are shown in Figure 15. The elliptical pattern on the flat, seen in the photograph of the flat, was produced by the droplet of lubricant. The wear scar can be seen as the light, horizontal streak at the center of the ellipse. Very clearly, sizeable deposits exist at the points where the wiper turned around. More of the same type of deposit is visible at the periphery of the lubricant droplet. Apparently the lubricant has the ability to suspend small particles of the contact deposit and transport them to the outer edge of the droplet. Detail in the wiper photo is far from clear, but careful examination reveals the same type of dark deposit at the very bottom of the wire, that is, around the area where the wire rubbed the flat. Another thin line of the contact deposit can be seen running horizontally across the wiper about one-half the way up its diameter. This line represents the point where the top of the lubricant droplet touched the wire.

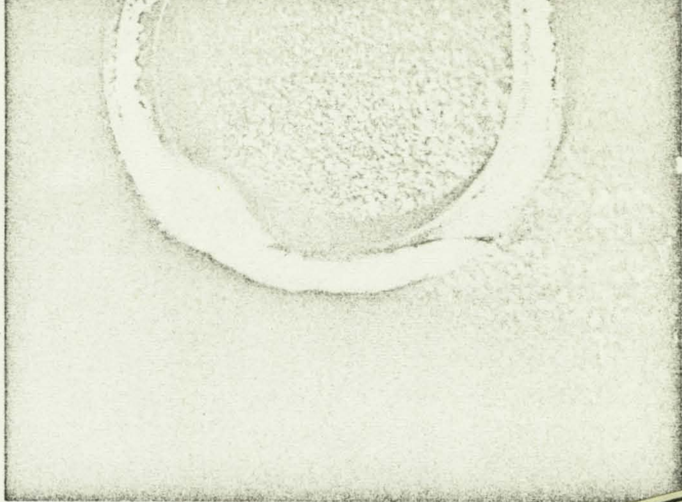
Thus, while the presence of the lubricant blend effectively diminishes the effect that the deposits have on the resistance behavior, it does not prevent the formation of deposits. It may be that the dilutory action of the lubricant would be sufficient to provide prolonged low-resistance performance of contacts under circumstances in which the offending vapors might eventaully be exhausted. Depending on such action may not be prudent. A safer policy would be to eliminate all potent sources of deposit-forming vapors from the environment of the slip-ring contacts.

CONCLUSIONS AND RECOMMENDATIONS

The complete experimental investigations of this program included several phases that were completed at the time the Interim Summary Report was prepared. Several phases received additional attention in a supplemental study, and are the subject of this report. Conclusions and recommendations for the portions of the program that were completed prior to May 31, 1968, were included in the Interim Summary Report. Since this is the final report for the program, however, the major recommendations from the earlier report, along with those from the supplemental study, are included here.

Off-Gassing of Organic Materials and the Resulting Contact Deposit Formation

The program afforded the opportunity to examine the off-gassing tendencies of almost all of the organic materials used in the slip-ring assembly, as well as the



10X

a. Wiper

10X

b. Flat

FIGURE 15. GOLD/NEYORO 28A CONTACTS AFTER OPERATING 336 HOURS LUBRICATED BY THE 75 PERCENT OS 124 AND 25 PERCENT MCS 210 BLEND AND SIMULTANEOUSLY EXPOSED TO VAPORS FROM KESTER AP-20

consequence of these tendencies insofar as contact deposit formation is concerned. Off-gassing tendencies of a few selected materials used in the platform but outside the slip-ring assembly were evaluated. The platform atmosphere was sampled, but measuring the contact-deposit tendencies of these off-gas products was not a part of the program.

First of all, the identity of the deposits found in actual slip rings is unknown. Limited attempts to identify them revealed that they contain large amounts of carbon, perhaps much more than 25 percent by weight. Hydrogen makes up a part of the deposits in the form of aliphatic C-H fragments. As revealed by their texture and color, the deposits originate from different off-gas products from one slip-ring assembly to another. In all the deposits examined from actual slip-ring assemblies, off-gas products of Loctite and Univis P-38 (bearing lubricant) are evident. Neither product should be used. Nylok* or Lockwell** might be suggested as a substitute for Loctite. A Krytox fluid***, such as Krytox 143AC, is a good substitute for the bearing lubricant of the slip-ring assembly with respect to contact-deposit tendencies. Its ability to lubricate the bearing was not measured.

Of the materials used in the fabrication or processing of the slip-ring assembly itself, the following conclusions and recommendations are made.

ES 218 and ES 209

As long as the contacts are Neyoro 28A wire and plated gold, ES 218 and ES 209 are satisfactory construction materials. A hardener content of 40 PHR (parts hardener per hundred parts resin) is recommended over 30 PHR.

ES 199 and ES 222

The off-gassing behavior of ES 199 and ES 222 is only slightly worse than that of ES 218 and ES 209. A substitution of ES 218 and ES 209 for ES 199 and ES 222 is in order if convenient. No strong need for substitution is indicated.

Solder Flux and Solder Flux Remover

Both Kester-115 Solder Flux****and Kester AP-20 Rosin Residue Remover**** pose a serious threat in the slip-ring assembly. Either a fluxless soldering system must be sought or great care must be exercised to remove the flux <u>and</u> the remover.

Solvents

Some solvents are contact-deposit formers; all can be responsible for spreading condensible materials over the slip-ring assembly. Great care must be exercised to prevent a build up of contamination in the solvents. The last rinse with a solvent ought to be done with fresh, clean material.

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*Nylok Division of U. S. Shoe Machinery.
**Standard Pressed Steel Company.
***E. I. duPont de Nemours & Company.
****Kester Solder Company, Chicago, Illinois.

The following conclusions and recommendations are made about organic materials used outside the slip-ring assembly but within the platform.

Stycast Materials

All of the Stycast formulations examined are satisfactory with the exception of formulations employing Catalyst 11. Such formulations should be avoided.

IM 1775 and IM 461

Torquer motors are potted with IM 1775 and IM 461. Both materials are heavy off-gassers of dibutyl phthalate. However, the phthalate does not contribute substantially to contact deposits nor to high contact resistance. No substitution of material is required.

Electrofilm Heater

The electrofilm heater is a potent source of deleterious off-gas products. A heater using nonorganic material is recommended. If such substitution is impossible or impractical, the present heater should be out-gassed thoroughly by heating to its maximum temperature before any internal parts of the platform are attached to the platform housing.

Off-Gas From Platform

Observing the contact-deposit-forming tendencies of the off-gas products of the platform taken as a single unit was not part of the program. The analysis of the composition of the atmosphere indicates that the atmosphere contains turpentine and tetrachloroethylene, which are off-gas products of materials that do lead to heavy contact deposits. The atmosphere also contains several types of alcohols, the contact forming tendencies of which are unknown. If the slip-ring contacts encounter any appreciable part of this atmosphere, the platform ought to be cleaned up from the standpoint of deleterious off-gas products.

Shipping Tube

Shipping tubes should be changed to glass or to some "inert" organic material such as Teflon.

Contact Lubrication

As a general conclusion, deposits that form on contacts as a result of exposure to organic vapors may be helpful or harmful to the contact performance. Under conditions in which the amount of the deposit does not become excessive, some of the deposits provided rather good lubrication of the contacts. The problem is that deposit formation at just the right ra e cannot be relied upon. Inadequately lubricated contacts, of the type used in slip-ring assemblies, seize or cold weld to an extent that they suffer unacceptably high wear. Electrodeposited gold prepared by Sel Rex processes* leaves a surface which has a significantly lesser tendency to suffer from wear effects under unlubricated conditions, but the wear is still severe for such deposits.

Of the many commercial lubricants evaluated, the one that provided satisfactory performance over the widest range of temperatures and wiper velocities was OS 124 (Monsanto Chemical). A blend of 75 percent OS 124 and 25 percent MCS 210 (Monsanto Chemical) extended the lower temperature limit and/or the maximum wiper velocity somewhat beyond that of OS 124. Furthermore there was no evidence to indicate that the high-temperature or low-wiper-velocity performance of the blend was not equal to that of OS 124. Thus, the blend of 75 percent OS 134 and 25 percent MCS 210 is recommended as the contact lubricant for slip-ring assemblies.

Wear-In Techniques

The results of these studies indicate that slip-rings lubricated by the blend of lubricants will probably perform satisfactorily without special conditioning. It is clearly indicated, however, that better low-temperature (~ room temperature or below) performance at wiper velocities greater than ~0.5 cm/sec can be expected if the contacts are run-in at 43 C for about 10^5 revolutions at a rotational speed that provides a wiper velocity of 0.9 cm/sec.

Roughening the surfaces of the rings, as is now done, is helpful in reducing the effects of hydrodynamic lift and should be continued. It is possible that an optimum roughness could be found in the event that operating conditions (i.e., wiper velocity or contact temperature) different than those currently envisioned for slip-ring contacts should arise.

Contact Shielding

The presence of the lubricant blend does not prevent the formation of friction polymers when organic vapors are introduced into the contact environment. It does delay the effect that such deposits have on the contact resistance. Although this type of protection might be adequate for a period in slip-ring assemblies, the prudent course is to eliminate all potent sources of organic vapors.

GBG/JBB:jls/jbs

*Sel Rex Corporation, Nutley, New Jersey.